Heavy-flavor measurements with the PHENIX experiment at RHIC

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DPG Spring Meeting
Cologne, Germany, March 8-12, 2004

Outline

- Motivation
- PHENIX @ RHIC
- Open heavy-flavor (charm) measurements
  - method
  - selected results
- Heavy quarkonia (J/ψ) measurements
  - method
  - selected results
- Summary
- Outlook

Motivation I: open charm production

- charm yield in heavy-ion collisions
  - production mainly via gluon-gluon fusion in the earliest stage of the collision

    ➡ **sensitive to initial gluon density**

  - additional thermal production at very high temperature
    $\rightarrow$ enhancement?

    ➡ **sensitive to initial temperature**

- propagation through dense medium
  - energy loss by gluon radiation?
    $\rightarrow$ softening of “charmed hadron” spectra?

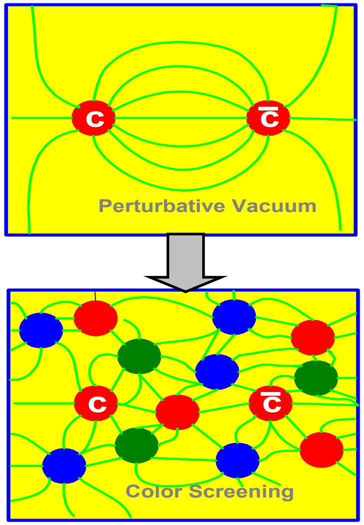
    ➡ **sensitive to state of nuclear medium**

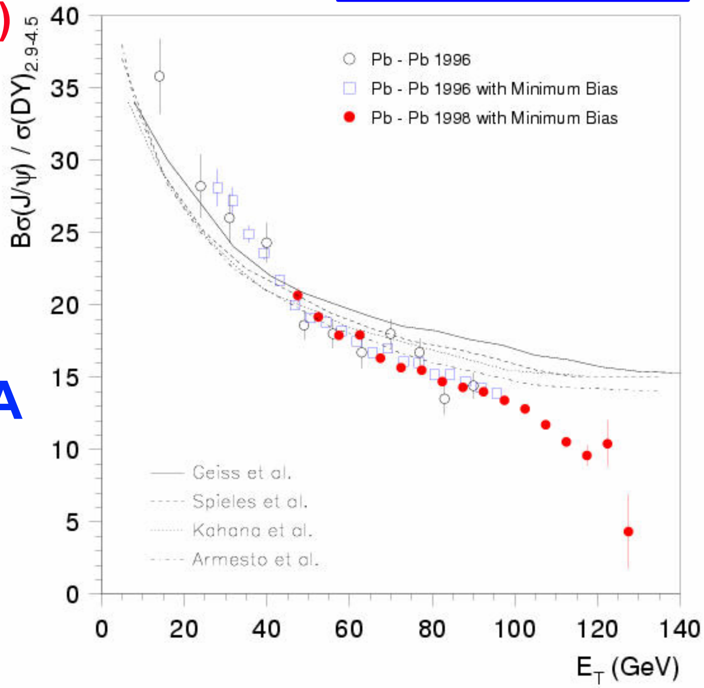
  - does charm flow?

    ➡ **sensitive to collectivity on partonic level**

Motivation II: charmonia (J/ψ)

- $c\bar{c}$: produced early / embedded in medium
- can form bound state: J/ψ
- deconfinement & color screening
  $\Rightarrow$ J/ψ suppression (Matsui and Satz, PLB176(1986)416)
- central Pb+Pb collisions at SPS
  - J/ψ suppression in excess of "normal" nuclear suppression (NA50: PLB477(2000)28)

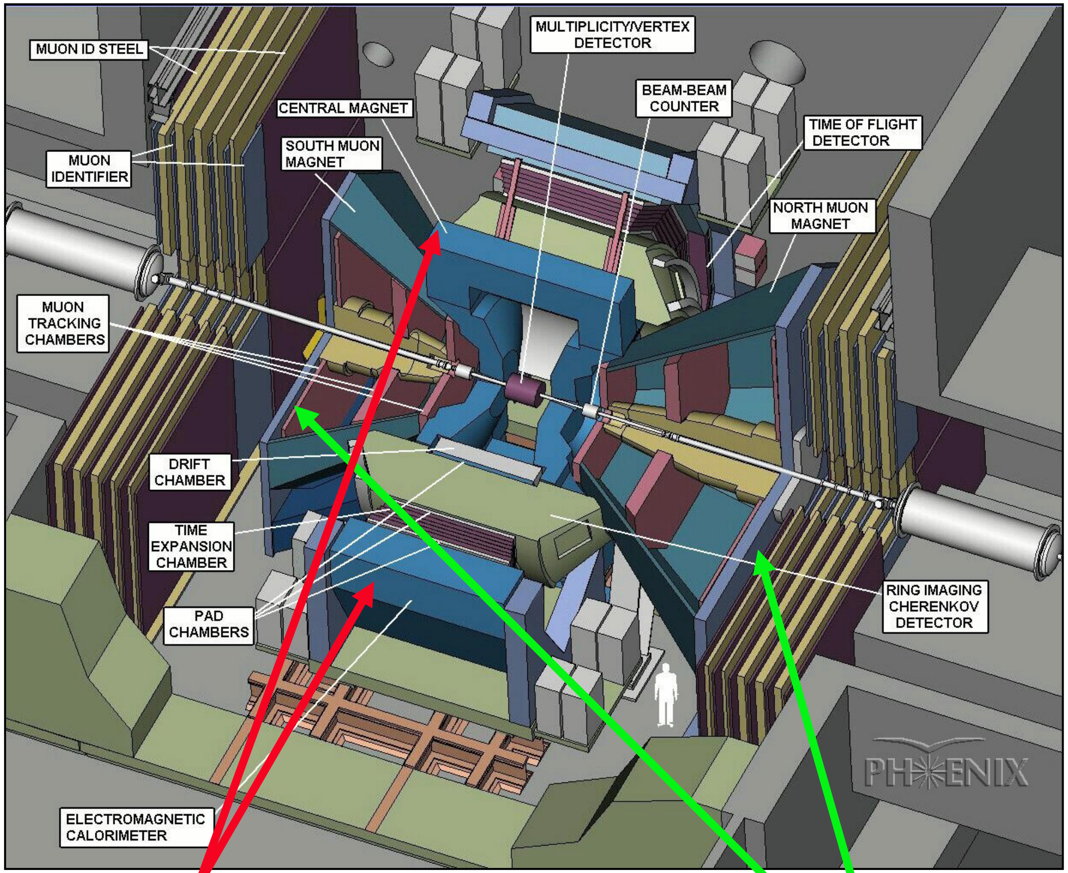




- prospects at RHIC
  - higher $c\bar{c}$ yield than at SPS
  - possible J/ψ enhancement due to $c\bar{c}$ coalescence as the medium cools
  - important to measure J/ψ in p+p and d+A to separate "normal" nuclear effects
    - (anti) shadowing
    - nuclear absorption in cold matter
  - open charm needed as baseline

PHENIX @ RHIC

- only RHIC experiment optimized for lepton measurements
- electrons: central arms
  - electron measurement in range:
    $|\eta| \leq 0.35$
    $p \geq 0.2$ GeV/c
- muons: forward arms
  - muon measurement in range:
    $1.2 < |\eta| < 2.4$
    $p \geq 2$ GeV/c

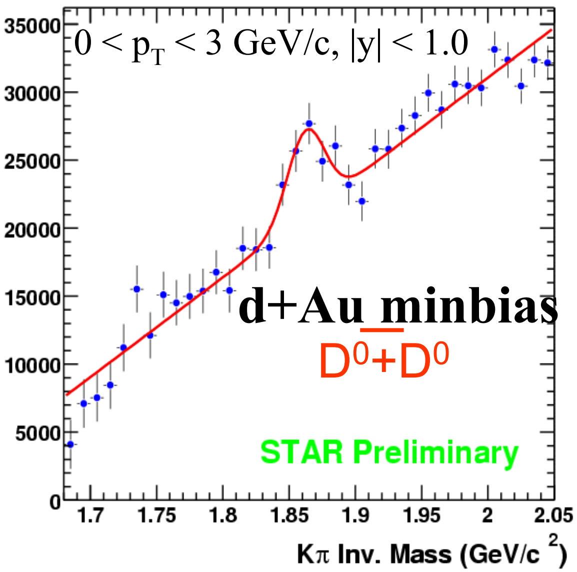


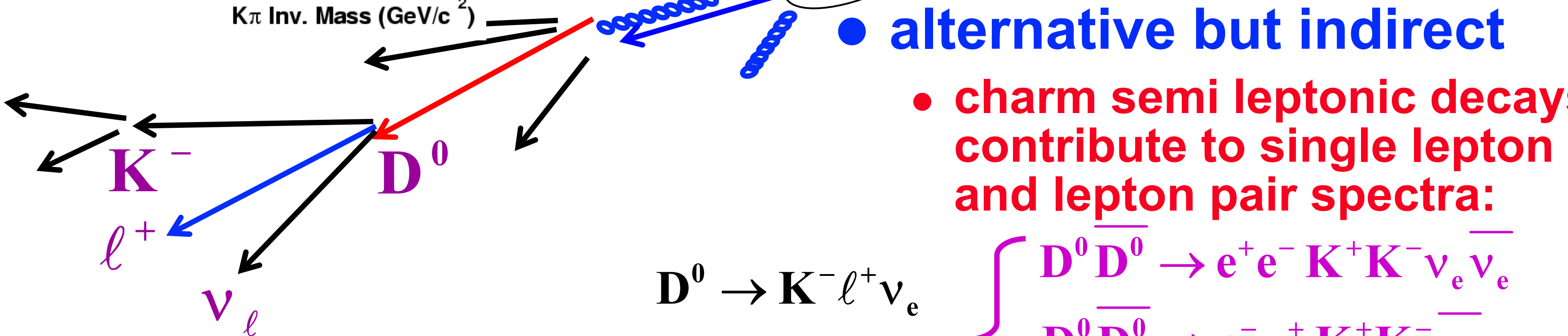
two central electron/photon/hadron spectrometers

two forward muon spectrometers

How to measure open charm

- ideal but very challenging
  - direct reconstruction of charm decays (e.g. $D^0 \rightarrow K^- \pi^+$)





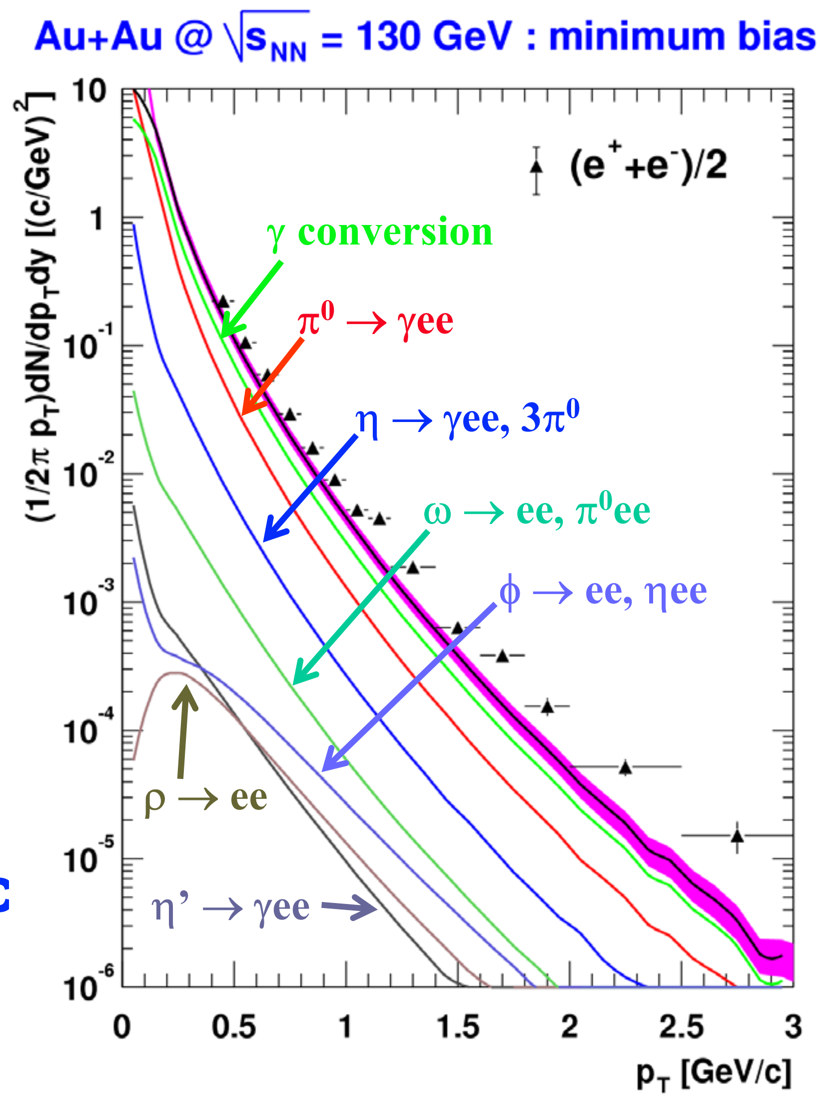
- alternative but indirect
  - charm semi leptonic decays contribute to single lepton and lepton pair spectra:

$$D^0 \rightarrow K^- \ell^+ \nu_e$$
$$\overline{D^0} \rightarrow K^+ \ell^- \overline{\nu}_\ell$$

$$\left\{ \begin{array}{l} D^0 \overline{D^0} \rightarrow e^+ e^- K^+ K^- \nu_e \overline{\nu}_e \\ D^0 \overline{D^0} \rightarrow e^- \mu^+ K^+ K^- \overline{\nu}_e \nu_\mu \\ D^0 \overline{D^0} \rightarrow \mu^+ \mu^- K^+ K^- \nu_\mu \overline{\nu}_\mu \end{array} \right.$$

Open charm via single electrons (I)

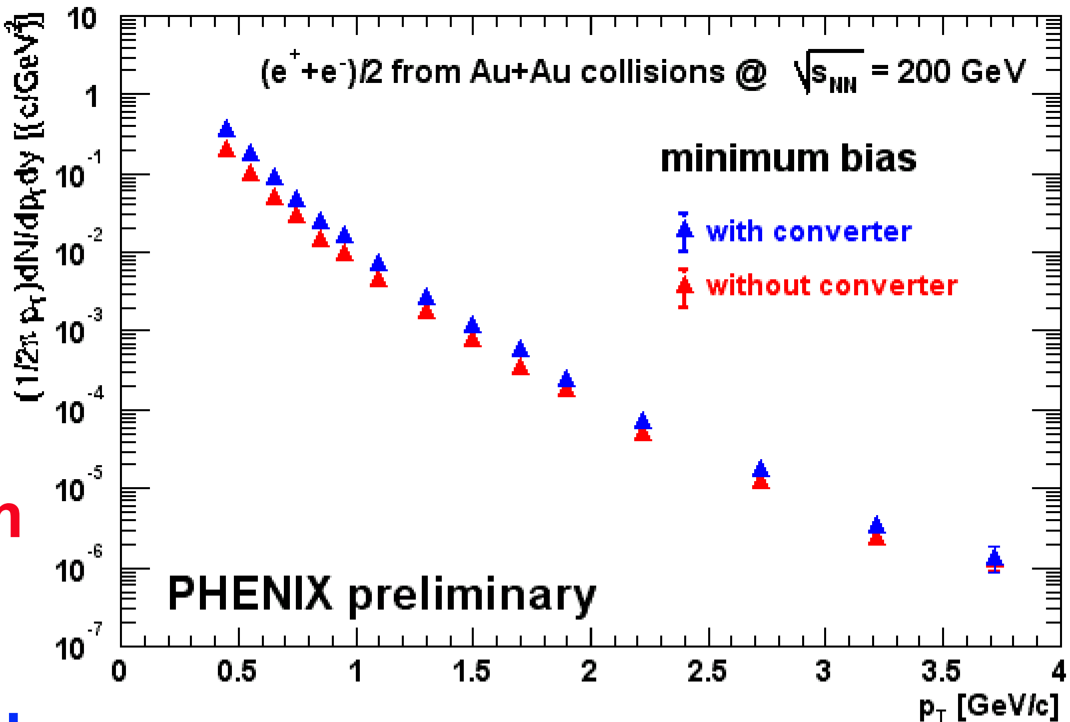
- cocktail method (example)
  - inclusive $e^{\pm}$ spectra from Au+Au at 130 GeV
  - use available data to establish "cocktail" of $e^{\pm}$ sources
    - dominated by measured π^0 decays and photon conversions
    - "photonic sources" are photon conversions and Dalitz decays
- excess above cocktail
  - increasing with p_T
  - expected from charm decays
- subtract cocktail from data
- attribute excess to semileptonic decays of open charm
- first "measurement" of open charm in HI collisions



PHENIX: PRL 88(2002)192303

Open charm via single electrons (II)

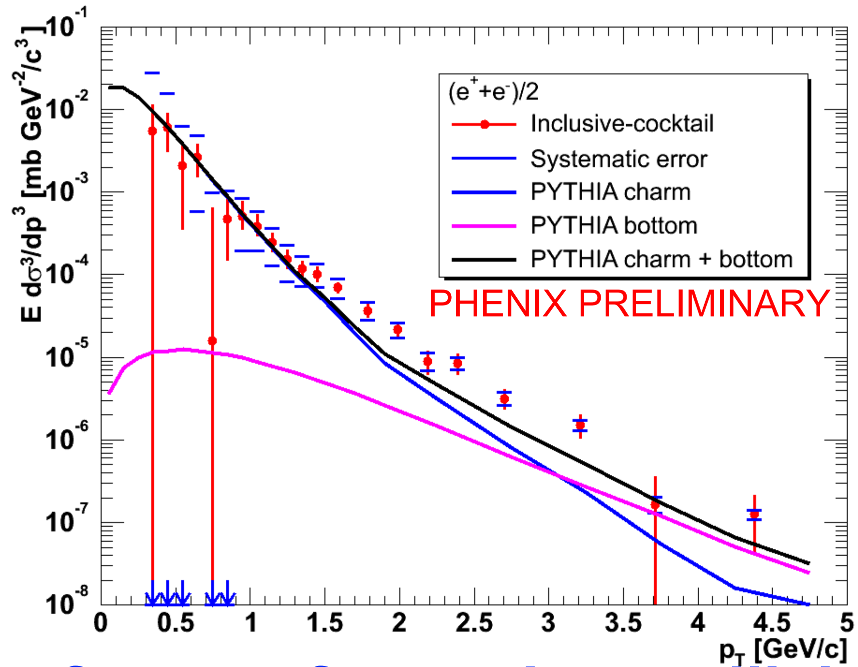
- converter method
  - add converter of known thickness to experiment
  - compare $e^{\pm}$ spectra with and without converter
  - separation of $e^{\pm}$ from photonic and non-photonic sources
- $e\gamma$ coincidence method
  - $e^{\pm}$ from photonic sources are correlated with a γ
  - separation of $e^{\pm}$ from different sources

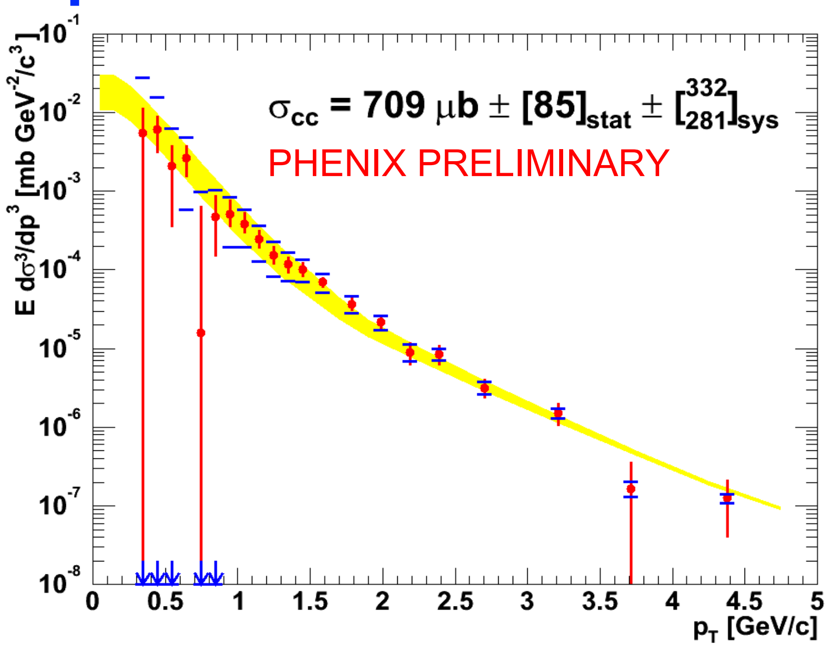


- three independent methods to measure electrons from non-photonic sources!

Open charm in p+p collisions at $\sqrt{s}$ = 200 GeV

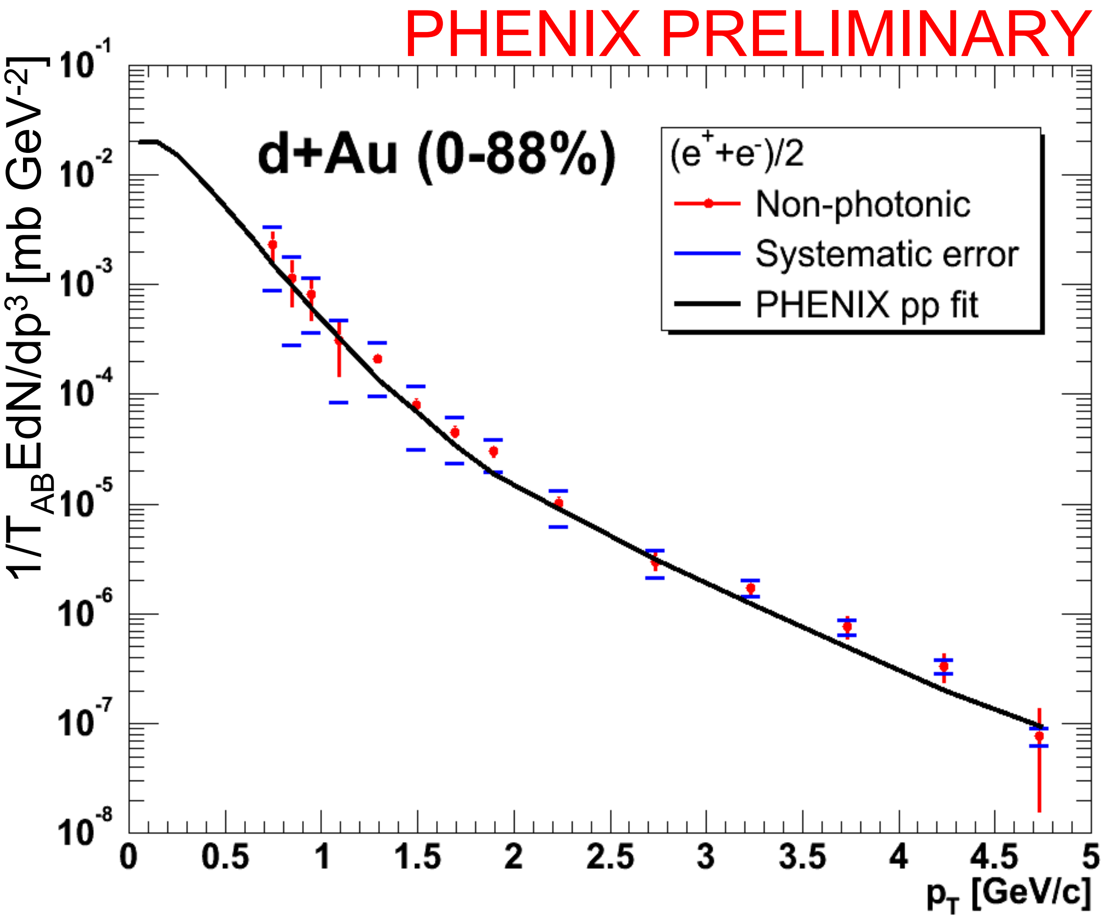
- non-photonic $e^{\pm}$ from p+p collisions at 200 GeV
- PYTHIA tuned to lower energy data ($\sqrt{s}$ < 63 GeV)
- for p_T > 1.5 GeV/c spectra are "harder" than PYTHIA prediction





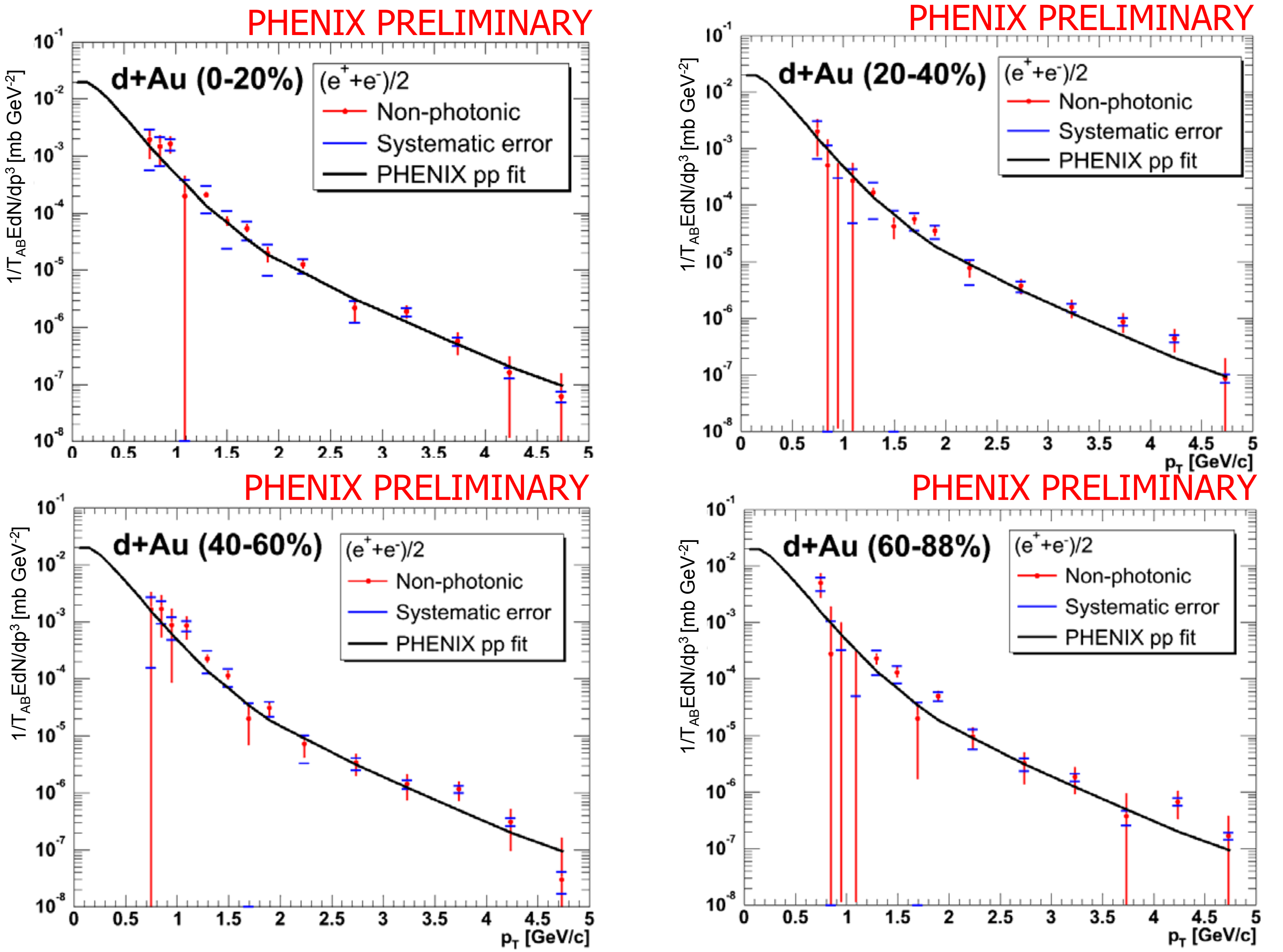
- reference for nuclear collisions
  - spectral shape
    - PYTHIA charm & bottom line shapes with normalizations as independent free parameters
  - total cross section
    - PYTHIA describes data at low p_T
    - use PYTHIA to extrapolate to full phase space

Open charm from d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

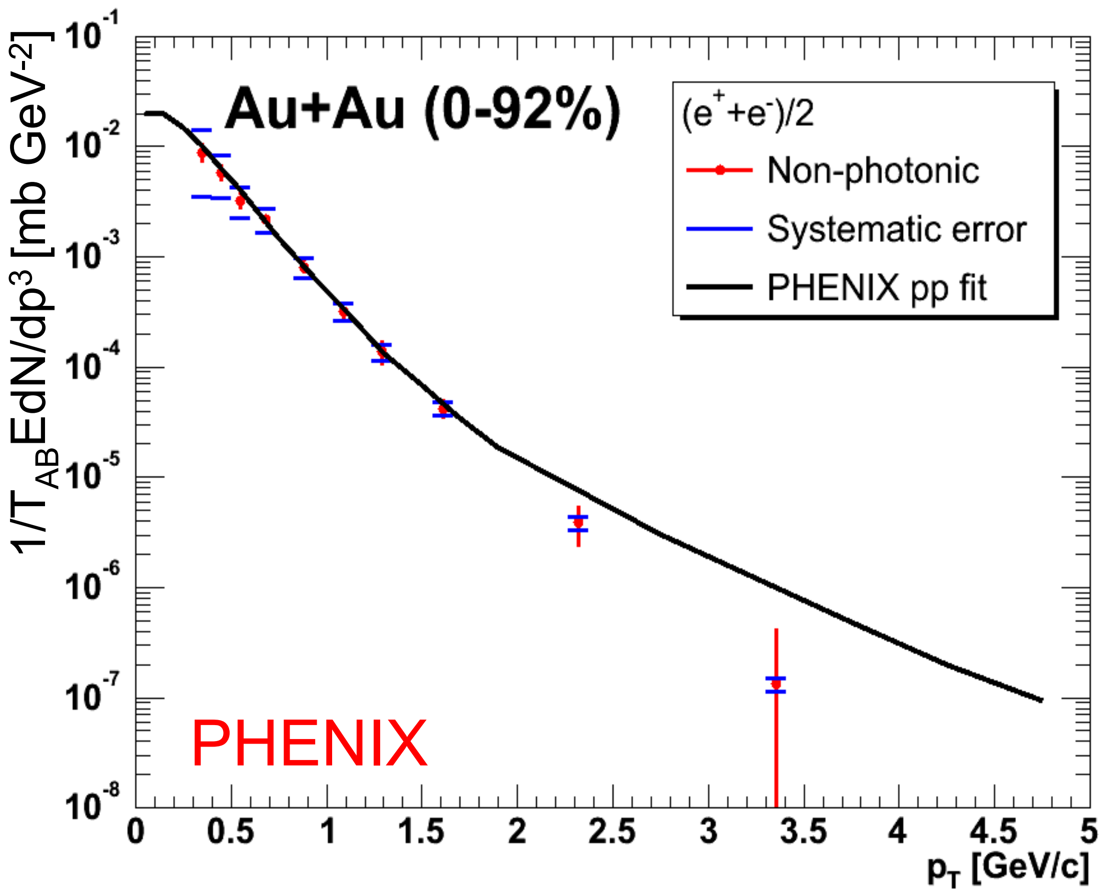


- **non-photonic $e^{\pm}$ from d+Au collisions at 200 GeV**
  - cross section divided by the nuclear overlap integral T_{AB} to account for the difference in system size between p+p and d+Au
  - very good agreement of d+Au data with the scaled p+p reference within uncertainties
  - no indication for strong cold-nuclear matter modifications
  - how about centrality dependence?

Centrality (in)dependence in d+Au collisions

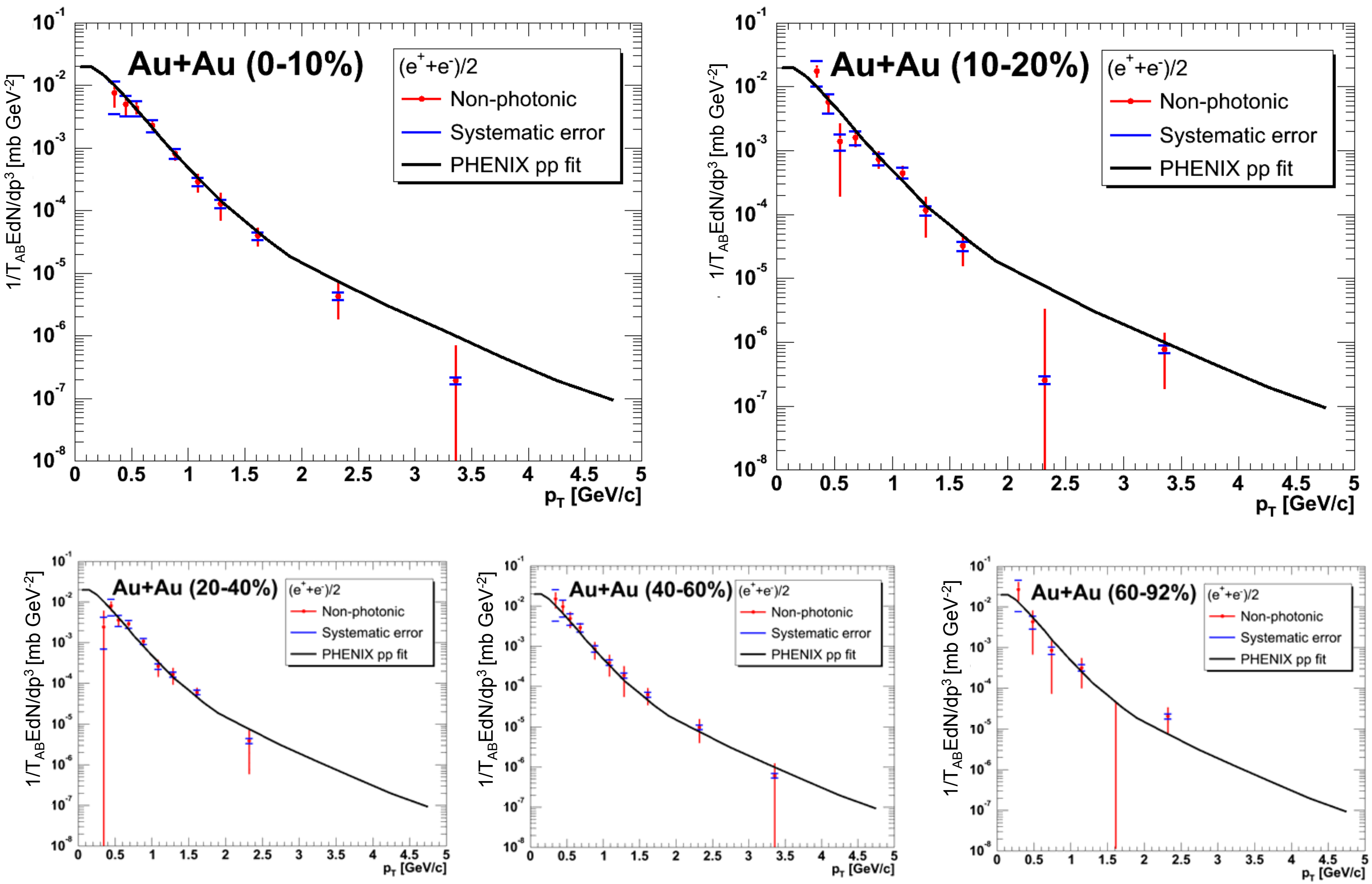


Open charm from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



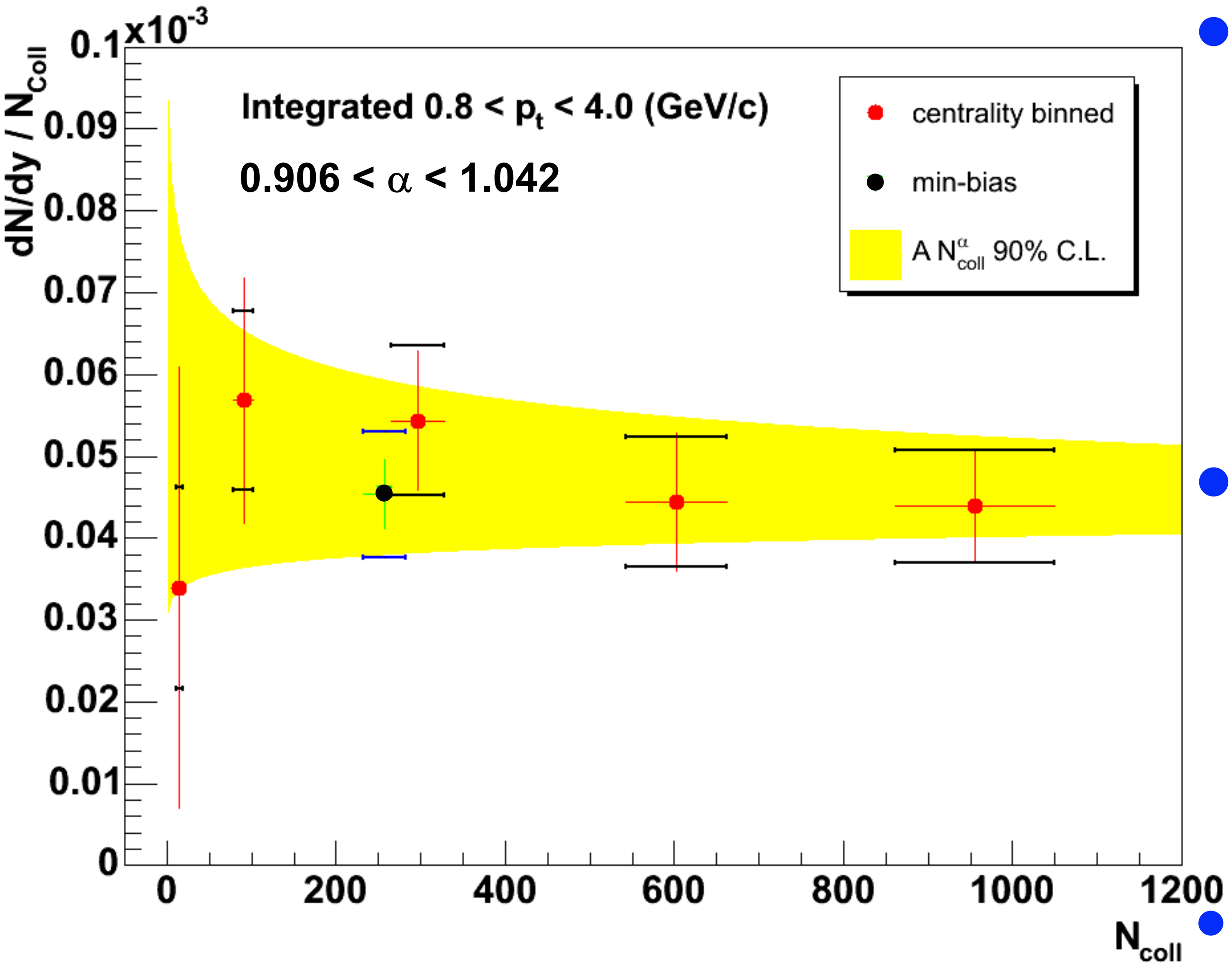
- non-photonic $e^{\pm}$ from Au+Au collisions at 200 GeV
  - cross section divided by the nuclear overlap integral TAB to account for the difference in system size between p+p and Au+Au
  - very good agreement of Au+Au data with the scaled p+p reference within uncertainties up to p_T = 1.5 GeV/c
  - at higher p_T more statistics is needed
  - no indication for strong medium modifications
  - how about centrality dependence?

Centrality (in)dependence in Au+Au collisions



- **more statistics is highly desirable!**

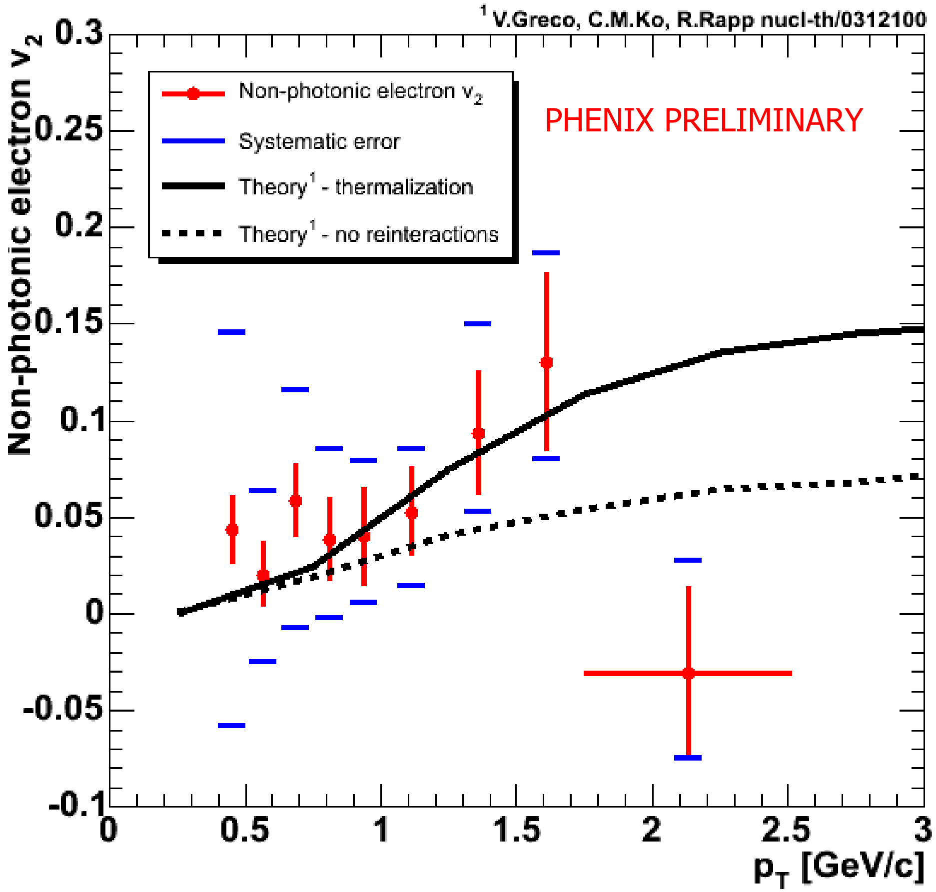
Binary collision scaling in Au+Au



- charm production seems to scale with T_{AB}, i.e. with the number of binary collisions N_{Coll}
- determine dN/dy of electrons in the measured range of p_T and test its consistency with $dN/dy = A\,(N_{coll})^{\alpha}$
- the 90 % Confidence Level on α is shown as yellow band

- binary scaling seems to work!

Does charm flow in Au+Au?



- charm flow could indicate partonic flow, i.e. collectivity on the parton level
- v_2 measures the 2^{nd} harmonic of the Fourier expansion of the azimuthal distribution of particle emission with respect to the reaction plane
- v_2 of $e^{\pm}$ from non-photonic sources is related to charm v_2!

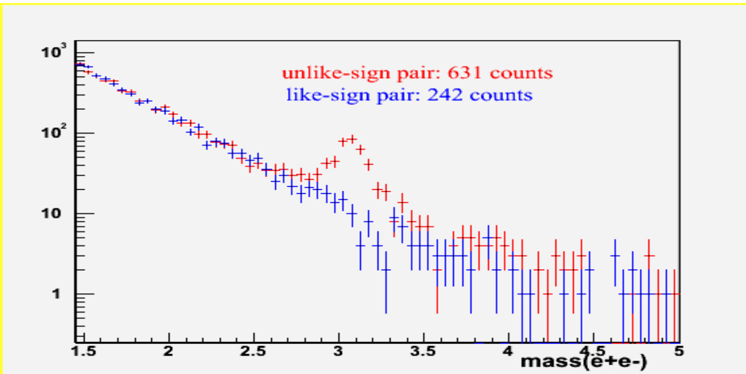
- uncertainties are too large to make a definite statement!

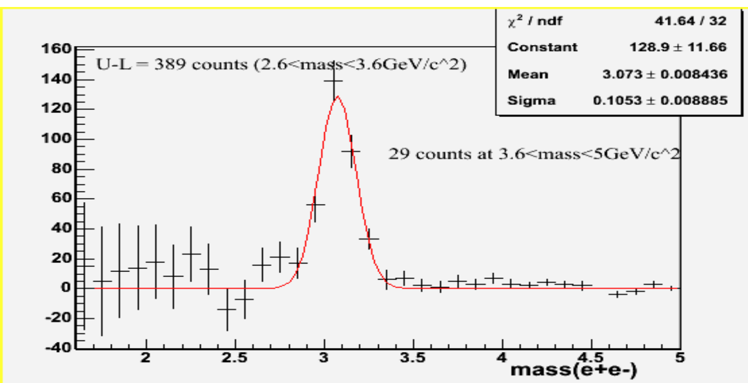
Summary (I): open charm at RHIC

- PHENIX: inclusive electrons in p+p, d+Au, and Au+Au at $\sqrt{s_{NN}} = 200$ GeV
- yield of electrons from non-photonic sources
  - consistent with binary scaling
  - no indication for strong enhancement / suppression of charm cross section in nuclear collisions
- statistics limited regarding
  - presence of spectral modifications in Au+Au (energy loss)?
  - charm flow in Au+Au?
  - to be answered by Run-4 data (currently ongoing)
- charm data as baseline for J/ψ measurements!

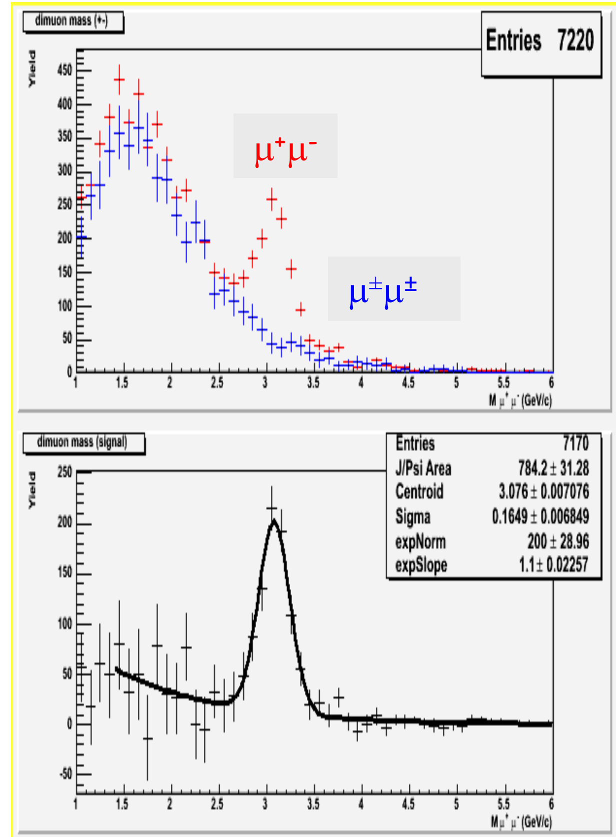
How to identify J/ψ (example: d+Au @ 200 GeV)

- J/$\psi \rightarrow e^+e^-$





- J/y$\rightarrow \mu^+\mu^-$ (north μ-arm)



- subtraction of combinatorial background by subtraction of like-sign dilepton mass spectra from unlike-sign spectra
- (small) physical background remains

J/ψ suppression/enhancement in Au+Au at RHIC?

- **preparing the case (need integrated luminosity!)**

Year	Ions	$\sqrt{s_{NN}}$	Detectors	J/Ψ
2000	Au-Au	130 GeV	Central (electrons)	0
2001 2002	Au-Au p-p	200 GeV 200 GeV	Central + 1 muon arm	13 + 0 [1] 46 + 66 [2]
2002 2003	d-Au p-p	200 GeV 200 GeV	Central + 2 muon arms	300+800+600 100+300+120
2004	Au-Au	200 GeV	! taking data !	~400+2x1600 ?

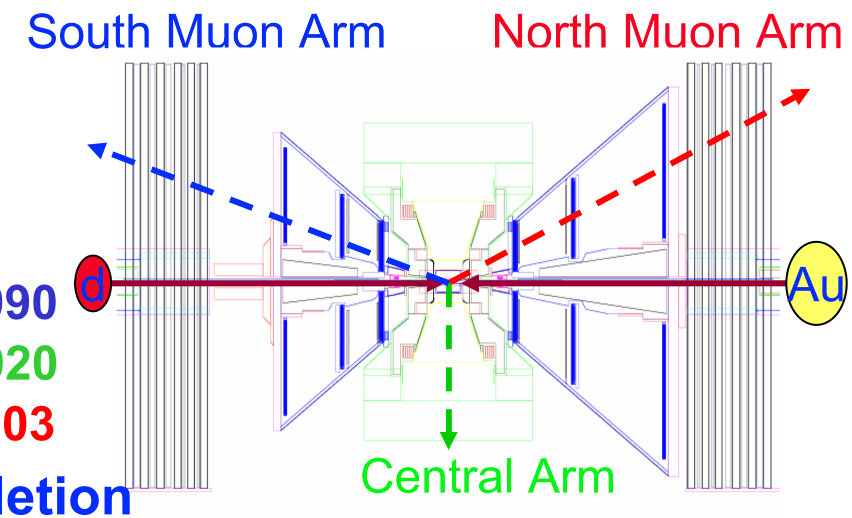
first J/ψ observation at RHIC

first sizeable samples in p+p & d+Au

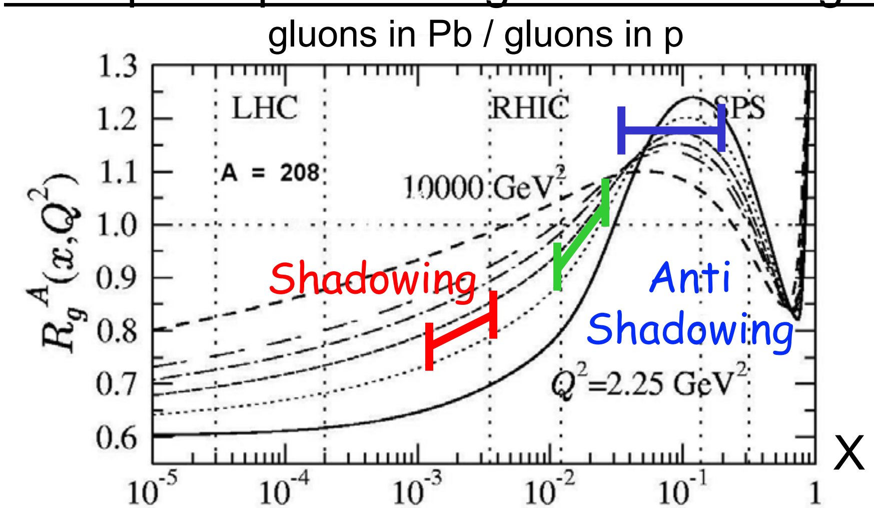
- **study modification of J/ψ production in cold nuclear matter: p+p versus d+Au!**

$J/\psi \rightarrow \mu^+\mu^-$ Analysis for d+Au & p+p

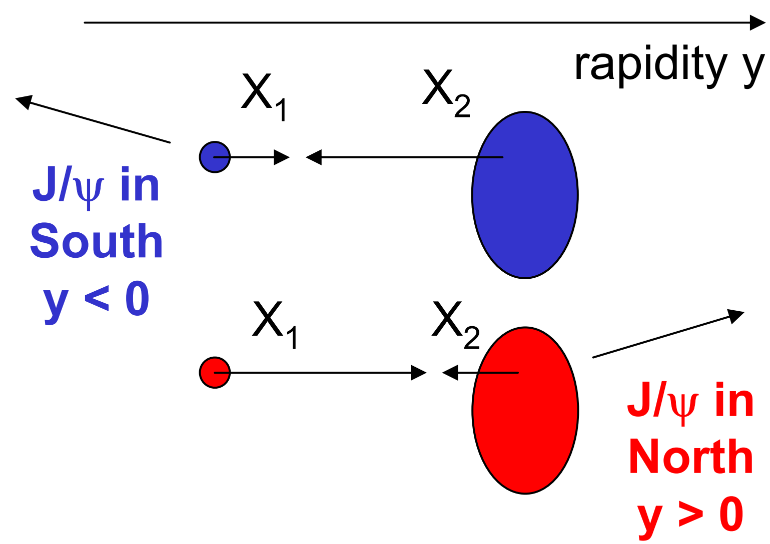
- **J/ψ mostly produced by gluon fusion $\rightarrow$ sensitive to gluon pdf**
- **three rapidity ranges probe different momentum fractions x_2 of Au partons**
  - **South ($y < -1.2$) : large X_2 (in gold) ~ 0.090**
  - **Central ($y \sim 0$) : intermediate X_2 ~ 0.020**
  - **North ($y > 1.2$) : small X_2 (in gold) ~ 0.003**
- **(anti)shadowing $\leftrightarrow$ (enhancement) depletion of (high) low momentum partons**



Example of predicted "gluon shadowing" in d+Au



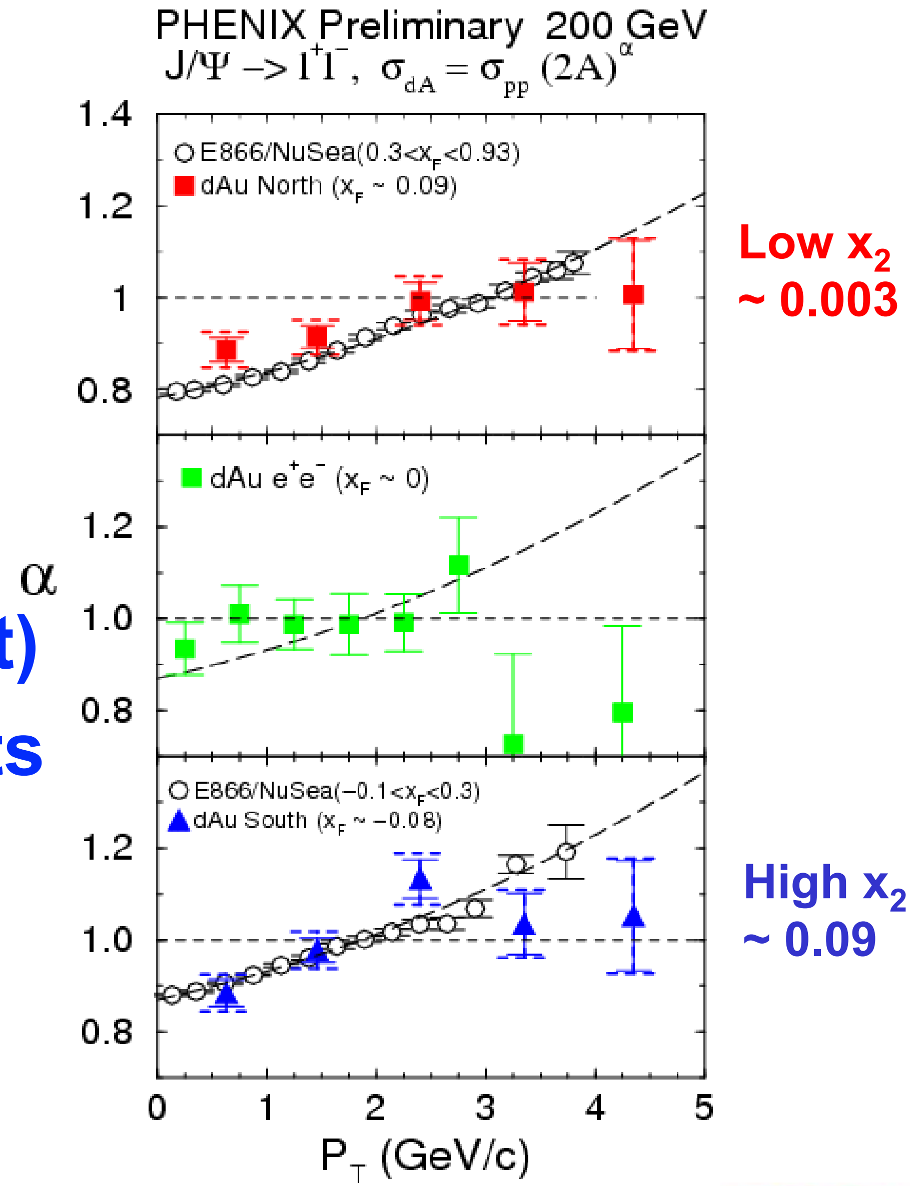
From Eskola, Kolhinen, Vogt: Nucl. Phys. A696 (2001) 729-746.



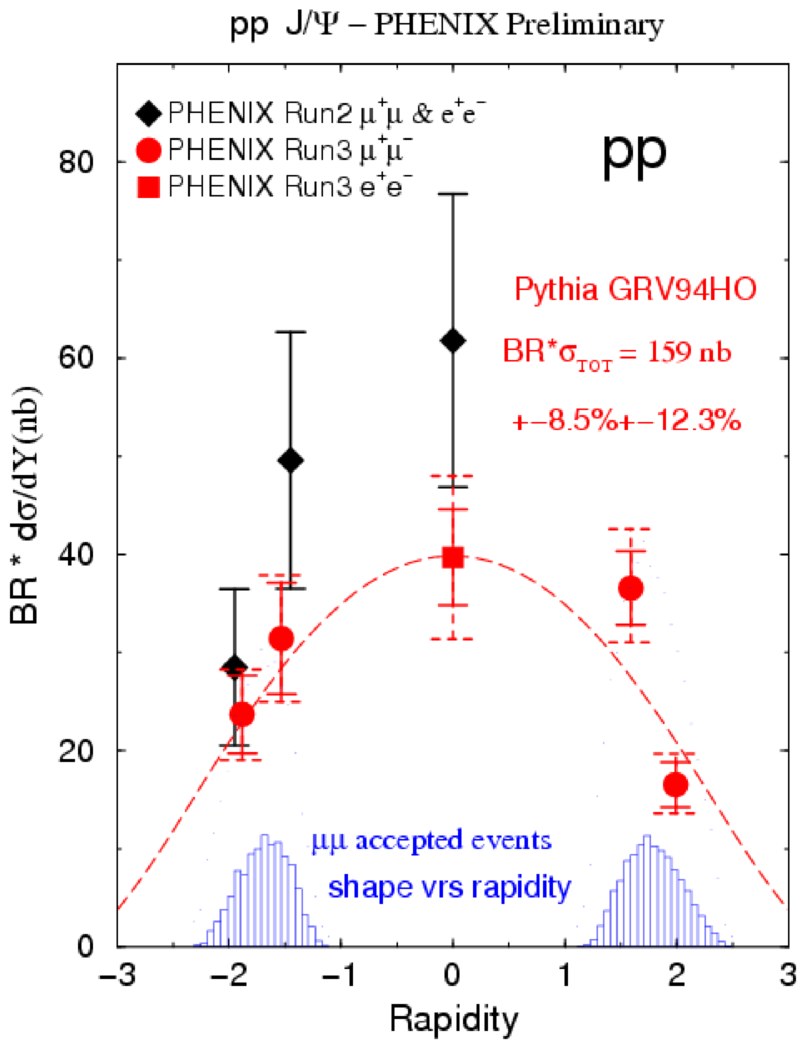
J/ψ ratio (d+Au / p+p) versus p_T

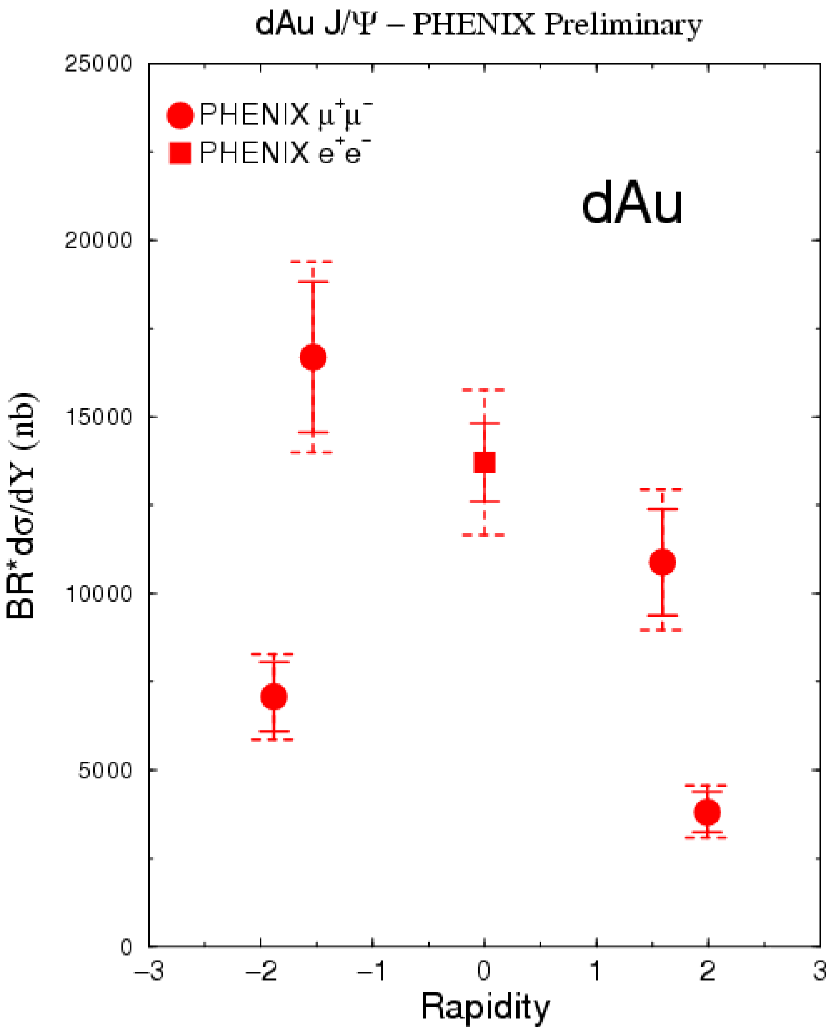
$$\sigma_{dA} = \sigma_{pp} \left(2 \times 197\right)^{\alpha}$$

- increase of α with increasing p_T → p_T broadening of J/ψ (initial state multiple scattering, Cronin effect)
- similar to measurements at lower energy (E866: $\sqrt{s}$ = 39 GeV)



J/ψ cross section versus rapidity

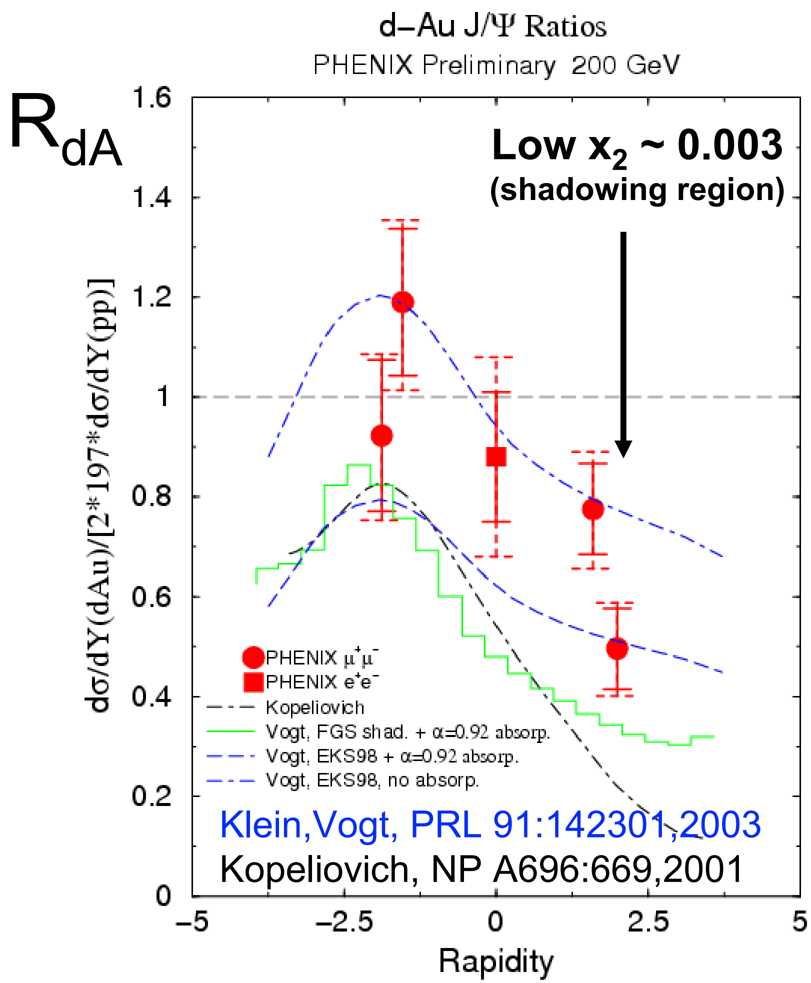


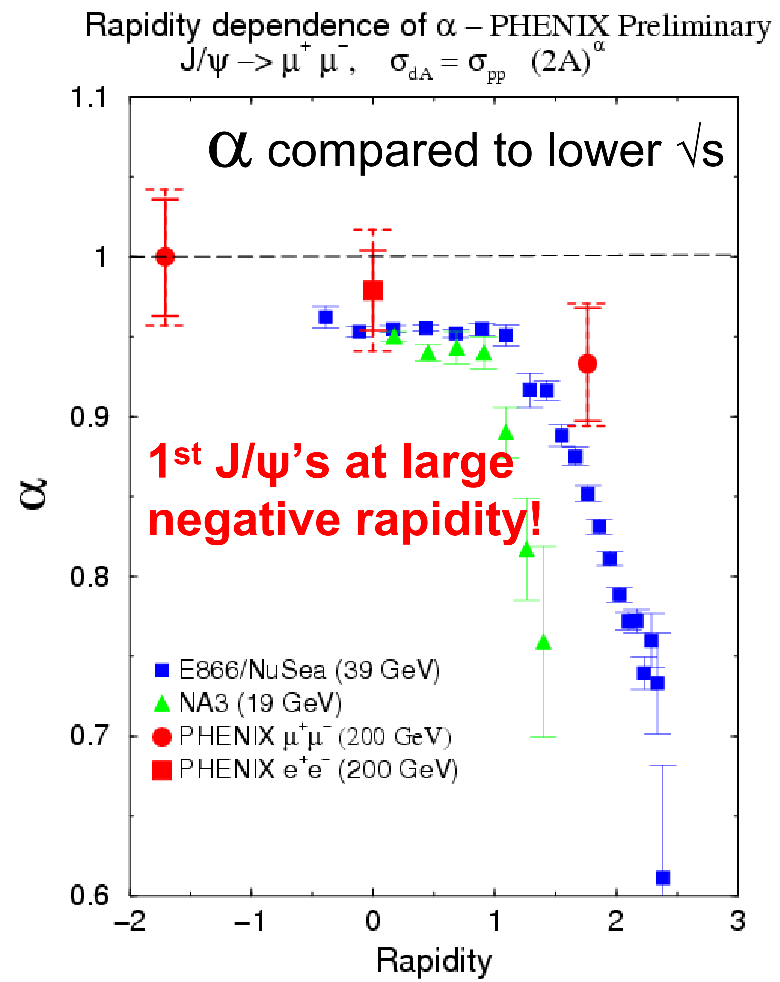


BR $\sigma_{pp}^{J/\psi}$ = 160 nb ± 8.5 % (fit) ± 12.3% (abs) - preliminary

J/ψ ratio (d+Au / p+p) versus rapidity

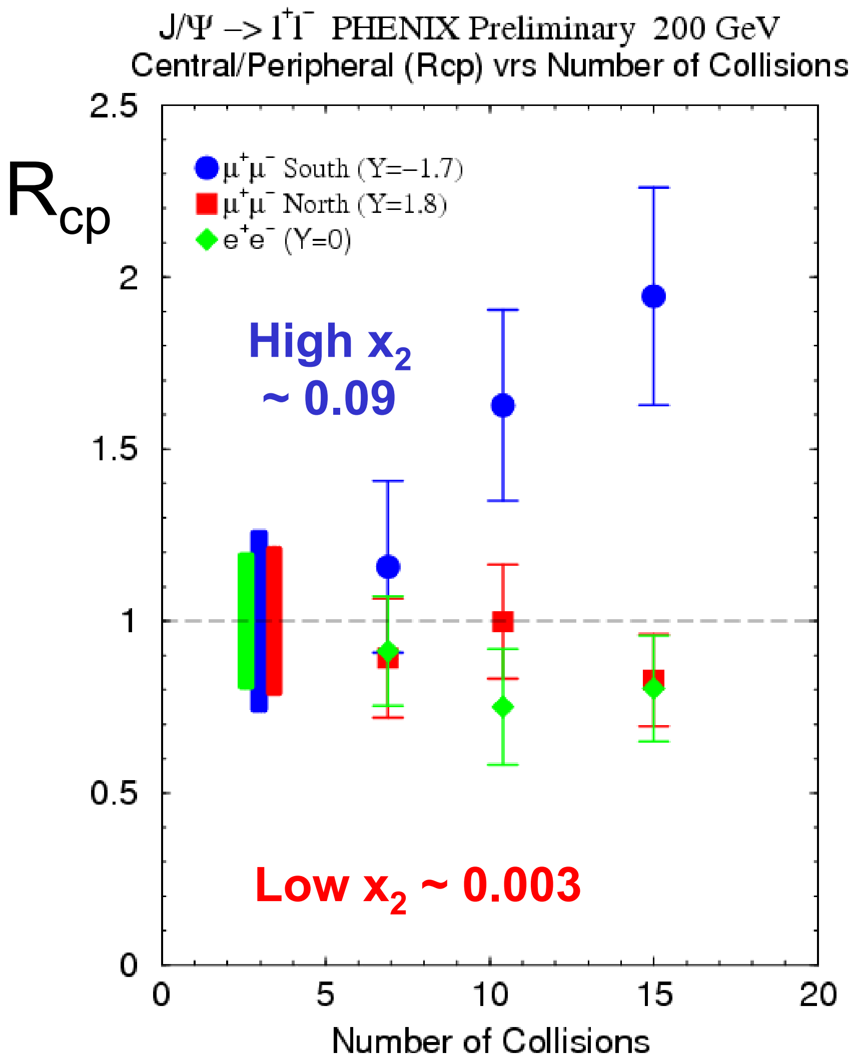
- data indicate nuclear effects (difficult to disentangle)!





- weak shadowing
- weak absorption

(central / peripheral) versus N_{coll}



- define four centrality classes for d+Au collisions
- determine N_{coll} for each class in a Glauber model
- calculate R_{cp}

$$R_{cp}(N_{coll}) = \frac{N_{J\psi}^{cent} \times < N_{coll}^{periph} >}{N_{J\psi}^{periph} \times < N_{coll}^{cent} >}$$

- low and medium x_2
  - weak nuclear effects
  - small (shadowing) centrality dep.
- high x_2
  - steep rise with centrality
  - how can antishadowing rise so steeply while shadowing does not?
  - final state effect in Au remnants (close to Au frame)?

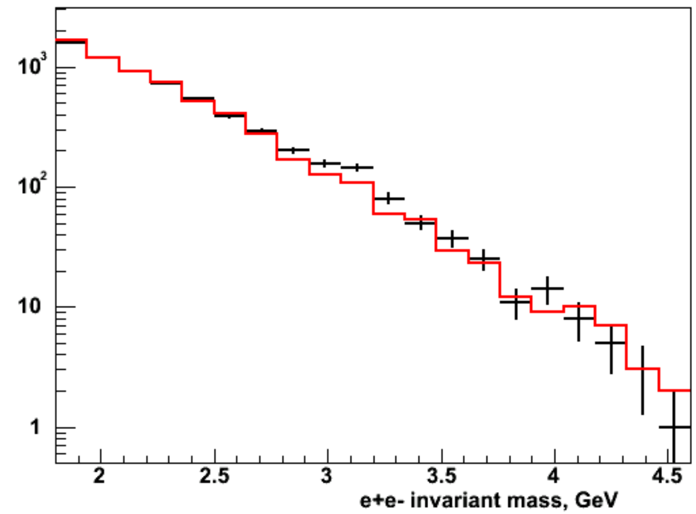
Summary (II): J/ψ at RHIC

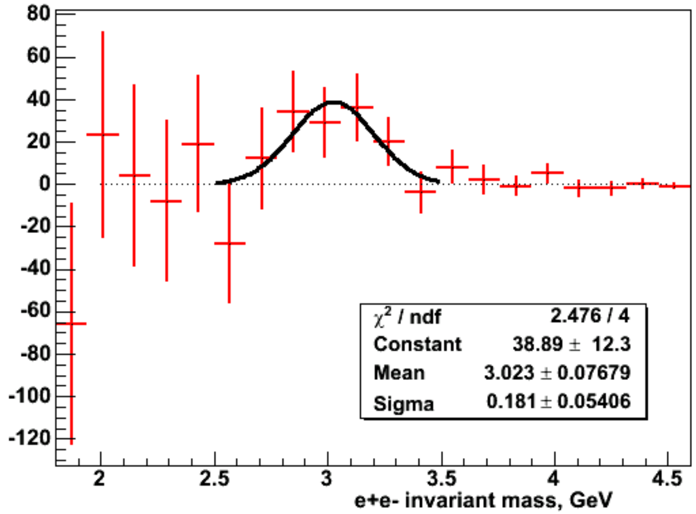
- cold nuclear matter effects have been observed in d+Au collisions
  - weak gluon shadowing
  - weak absorption

    } smaller than expected from lower energy data
  - p_T broadening: similar to lower energy data
- disentangling these effects requires more data
- modest baseline for J/ψ measurements in Au+Au collisions is available: the stage is set!
- Run-4 (Au+Au at 200 GeV) is currently ongoing!

Outlook

- J/ψ production in Au+Au at 200 GeV (Run-4)
- a first J/ψ signal in the dielectron channel
- stay tuned!





The PHENIX Collaboration

12 Countries; 58 Institutions; 480 Participants*

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*as of January 2004